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# A review on sustainable design of renewable energy systems

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ABSTRACT

This paper reviewed the state of the art in designing renewable energy systems specifically solar-based energy system, ground source-based system and day-lighting system, to gain optimum performances in sustainable buildings. Efficiency of each of these systems in reducing resource consumption was evaluated. Geometric conditions have a determining effect on the performances of solar-based energy system and day-lighting system. In solar-based energy system, designing factors, such as system selection, building's orientation, installation location, area of installation, tilt angle and surface temperature, are needed to be considered. Factors of day-lighting system, such as fenestration option, material, area or size, shape, orientation, position, ceiling and shading devices, are needed to be designed carefully to optimize the quality of the luminous environment for occupants. For ground source-based energy system, season condition, operating condition, mode of system, selection of compressor, ground heat exchanger, pump, are important to improve system's performance and reduce cost.



**Contents**



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## 1. Introduction

Buildings as big energy-consuming systems require large amount of energy to operate. Globally, buildings are responsible for approximately 40% of total world annual energy consumption, in the form of lighting, heating, cooling, and air conditioning [1]. Sustainable design and construction are gaining significant momentum in the construction industry. Designers and owners are learning that with smart design, buildings can save energy and have a decreased impact on the environment [2]. Sustainable buildings with renewable energy systems are trying to operate independently without consumption of conventional resources. This reduces impact on the environment throughout buildings' lifecycle.

Renewable energy is a significant approach to reduce resource consumption in sustainable building. Renewable energy is the energy that is generated from natural resources, such as wind, solar, rain, tides and geothermal heat. Currently, three systems have been receiving wide concern, including solar-based energy systems, ground source-based energy systems and day-lighting systems [3]. These renewable energy systems have attracted much attention from designers and engineers, and they could cover most or all of the energy usage in buildings [4–8].

This paper reviews the state of the art of three renewable energy systems, namely solar-based energy system, ground source-based system and day-lighting system, with optimum performances to reduce conventional energy usage in sustainable buildings.

The objectives of this review are:

- To investigate influences of geometric conditions and designing factors to the performance of solar-based energy system, including photovoltaic (PV) system and solar chimney system;
- To find out a better design approach to improve the performance and reduce cost of ground source-based energy system; and
- To provide a guide of typical day-lighting systems, including side-lighting system and top-lighting system, to optimize the quality of luminous environment for occupants in buildings.

## 2. Solar-based energy systems

### 2.1. Photovoltaic system

#### 2.1.1. Theory

The importance of PV was once a questionable issue when fossil fuel was seen as an endless source of energy. With growing recognition of the environment impact and the economic instability due to oil and gas price fluctuations, PV development has the interest of almost all sectors [9]. The production of solar cells has grown at an average annual rate of 37% in past decade, i.e. from 77.6 MWp in 1995 to 1817.7 MWp in 2005, and at an average annual rate of 45% from 287.7 MWp in 2000 to 1817.7 MWp in 2005 [10].

Currently, PV market consists of a wide range of material and manufacturing processes leading to knowledge transfer regarding efficiency and suitability of available technologies. Three generations of PV are produced as the development of technology [9]. The first PV generation is governed by single-junction crystal solar cell based on silicon wafers (single and multi crystalline silicon). The second generation technologies are based on single junction devices aiming to optimize material usage while upholding the efficiencies achieved earlier. This generation comprises of CdTe, CiGS and a-Si. While the second generation emphasis is on the reduction of material cost by embracing thinner films, the third generation approach is more concerned with double, triple junction and nanotechnology, which are all showing promising results efficient cells at lowest cost. The aim of continuous development of PV technology is not only to improve the efficiency of the cells but also to reduce production cost of the modules, hence make it more feasible for various applications [11–14].

Building-integrated photovoltaic (BIPV) is a PV application close to being capable of delivering electricity at less than the cost of grid electricity to end users in certain peak demand niche markets [15]. These PV panels are largely used on rooftop, also on vertical wall and double glazing window, to gain direct heat from the sun. Fig. 1 shows a schematic of BIPV system on vertical wall, rooftop, and window glazing.

To improve the efficiency of PV panel, a building integrated photovoltaic thermal (BIPVT) system is proposed. BIPVT system appears as an exciting new technology as it merges PV and thermal systems, providing simultaneously both the electrical and the thermal energy onsite. This system integrates roof, photovoltaic, thermal and insulation into a single product [16]. The attractive features of the BIPVT system are [17]:

- It is dual-purpose: the same system can be used to produce electricity and heat output;
- It is efficient and flexible: the combined efficiency is always higher than using two independent systems and is especially attractive in BIPV when roof spacing is limited;
- It has a wide application: the heat output can be used both for heating and cooling (desiccant cooling) applications depending on the season and practically being suitable for domestic applications; and
- It is cheap and practical: it can be easily retrofitted/integrated to building without any major modification and replacing the roofing material with the BIPVT system can reduce the payback period.

BIPVT products can be classified into four types: liquid collector, air collector, ventilated PV with heat recovery, and concentrator. These four types have their own advantages and disadvantages, and details can be found in Ref. [17]. Fig. 2 shows schematic of a typical air-based open-loop BIPVT system.

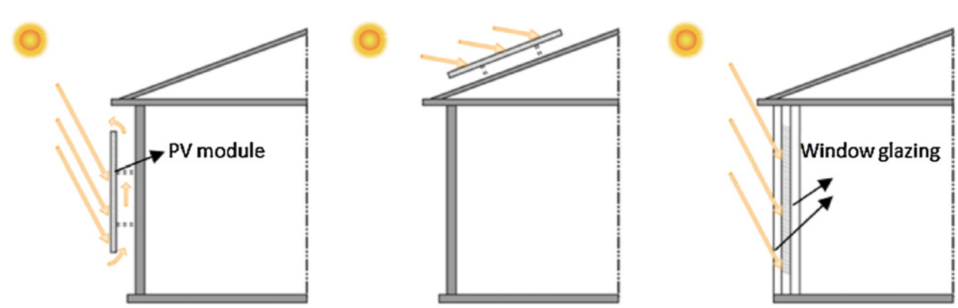


**Fig. 1.** Schematic of BIPV system on vertical wall (left), rooftop (middle), and double-glazing window (right).

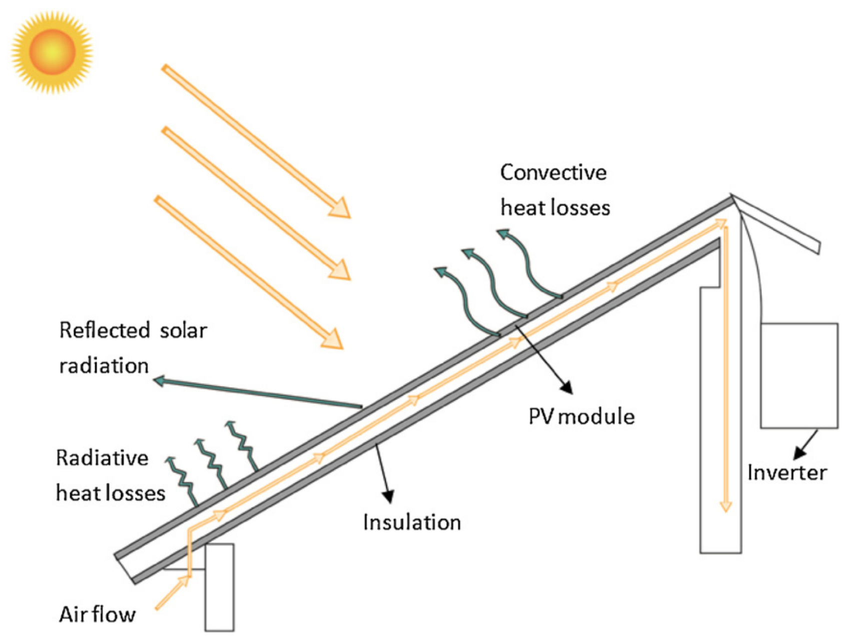


**Fig. 2.** Schematic of a typical air-based open-loop BIPVT system.

*2.1.2. Design and energy saving*

Two kinds of influencing factors would have effects to the performance of PV system. The first kind is geometric conditions, such as local weather condition, altitude and latitude. The geometric conditions cannot be changed and determine the optimum performances can be gained by PV systems. Pre-designing should be carefully taken to ensure that the geometric conditions are suitable for PV system. The second kind focused on in this paper is designing factors, such as system selection, building's orientation, installation location, area of PV panel and tilt angle. These influencing factors can be analyzed carefully to obtain an optimum performance of PV system. A summary of research on PV systems designing is listed in Table 1.

BIPV system and BIPVT system are two kinds of systems can be selected for sustainable building. Besides conventional function of electricity production, BIPVT also provide thermal heat for heating or hot water. Guiavarch and Peuportier [18] presented that efficiency increases from 14% to 20% when a ventilated PV module is used. If buildings are limited in rooftop, BIPVT system is a better choice because it could not only increase efficiency of electricity produce, also get more energy from hot air or hot water when ventilation is allowed under PV module.

Some influencing factors are significant to the performance of PV system. Chow et al. [19] obtained that weather conditions and operating model of buildings have a determining effect on the PV productivity. Area of solar cell in PV system also has a significant effect on total heat gain as solar heat gain is the major component of the total heat gain [20]. Anderson et al. [21] showed that key design parameters such as the fin efficiency, thermal conductivity between PV cells and their supporting structure, and lamination method have significant influences on both electrical and thermal efficiency of BIPVT systems.

The power output of PV module was characterized depending on incidence angle and the orientation. Song et al. [22] analyzed the performances of PV modules by using a full-scale mock-up model in South Korea. It was obtained that: (1) the PV module with a slope of 30°, facing south, provided the best power performance according to an annual power output, producing about 2.5 times higher power output than that with the vertical module; and (2) the increased inclined slope of the PV module resulted in reduced solar energy transmission, which producing a significant reduction of power output for the PV module with a slope over 70°. Yoon et al. [23] experimentally gained that energy saving can be improved up to 47% by changing orientation and its shading effect originated from the building mass. Sun et al. [15] presented that optimum performance of buildings in Hong Kong gained by a tilt angle from 30° to 50° and orientation of south or southwest.

The efficiency of PV module is also dependent on its surface temperature. Experiments taken by Park et al. [24] showed that power decreased about 0.48–0.52% per the 1 °C increase of PV module temperature. Also they suggested that property of the glass used for the module affects the PV module temperature followed by its electrical performance. Fossa et al. [25] obtained that proper selection of separating distance and heating configuration can noticeably decrease surface temperatures.

## 2.2. Solar chimney

*2.2.1. Theory*

A solar chimney is essentially divided into two parts, one – the solar air heater (collector) and second – the chimney [27]. Two configurations of solar chimney are usually used: vertical solar chimney with vertical absorber geometry, and roof solar chimney. Schematics of these two kinds of solar chimney are shown in Fig. 3. For vertical solar chimney, vertical glass is used to gain solar heat. Temperature difference between vertical glass duct and interior room produces a pressure difference. And interior air will go out through inlet because of this pressure difference. The temperature difference is a determining factor of performance of solar chimney. For roof solar chimney, solar collector plays the same role as vertical glass in vertical solar chimney. Air flow will encounter resistance because of additional bends of duct.

Advantages and disadvantages exist for both of vertical solar chimney and roof solar chimney, which are shown in Table 2 [28].

*2.2.2. Design and energy saving*

Designing a solar chimney includes height, width and depth of cavity, type of glazing, type of absorber, and inclusion of insulation or thermal mass [28]. Besides these system parameters, other

**Table 1**
Summary of research on PV systems designing.

| Method | System | Location | Major parameters | Results | Major findings/limitations | Ref. |
|---|---|---|---|---|---|---|
| Numerical | BIPV | Hong Kong | Facing South<br>Tilt angle of 10° | 76.8 kWh/m$^2$ | • Orientations of south and southwest are two better choice; and<br>• Optimum tilt angles vary from 30° to 50°. | [15] |
| Both[a] | BIPV | South Korea | Facing 50° southwest<br>In vertical window | 580.5 kWh/kWp/year | • Energy saving can be improved up to 47% by changing orientation and its shading effect originated from building mass. | [23] |
| Numerical | BIPVT | India | 65 m$^2$ PV effective area<br>Facing south<br>Tilt angle of 35° | 16,209 kWh/year electricity<br>1531 kW/year thermal exergy | • The series combination is more suitable for BIPVT as rooftop. | [16] |
| Numerical | BIPV | Hong Kong | In vertical window | 175.3–214 kWh/m$^2$ | • Area of solar cell in the PV module has significant effect on total heat gain; and<br>• Solar cell energy efficiency and PV module's thickness have only a little influence on total heat gain. | [20] |
| Numerical | BIPV | Macau | 260 m$^2$ PV area | Maximum output of 23 kWp | • Weather condition and operating model of building have a determining effect on PV productivity. | [19] |
| Numerical | BIPV | South Brazil | 8000 m$^2$ roof cover | 1 MWp | N.A. | [26] |
| Both | BIPVT | New Zealand | 0.98 m$^2$ area | Maximum value of 500–600 W/m$^2$ | • Key design parameters, such as the film efficiency, the thermal conductivity between supporting structure, and the lamination method, have a significant influence;<br>• BIPVT could be made of lower cost materials, such as pre-coated color steel, without significant decreases in efficiency.<br>• Integrating BIPVT into the building could result in a lower cost rather than onto the building. | [21] |
| Both | BIPV/BIPVT | Paris | In vertical window (162 m$^2$)<br>On roof south oriented with a 45° slope (160 m$^2$) | 334,960 kWh/year for vertical window system;<br>14,320 kWh/year for roof system | • Efficiency increases from 14% to 20% when a ventilated PV module is used | [18] |
| Experimental | BIPV | Italy | On vertical wall<br>0.64–1.28 m$^2$ | N.A. | • Selection of separating distance and heating configuration can noticeably decrease surface temperature and hence enhance the conversion efficiency of PV modules. | [25] |
| Experimental | BIPV | South Korea | In vertical window | N.A. | • Power decreases about 0.48–0.52% per 1 °C increase of PV module temperature;<br>• Property of the glass used for module affects PV module temperature also its performance. | [24] |

[a] Both means both experimental and numerical methods are used in references.

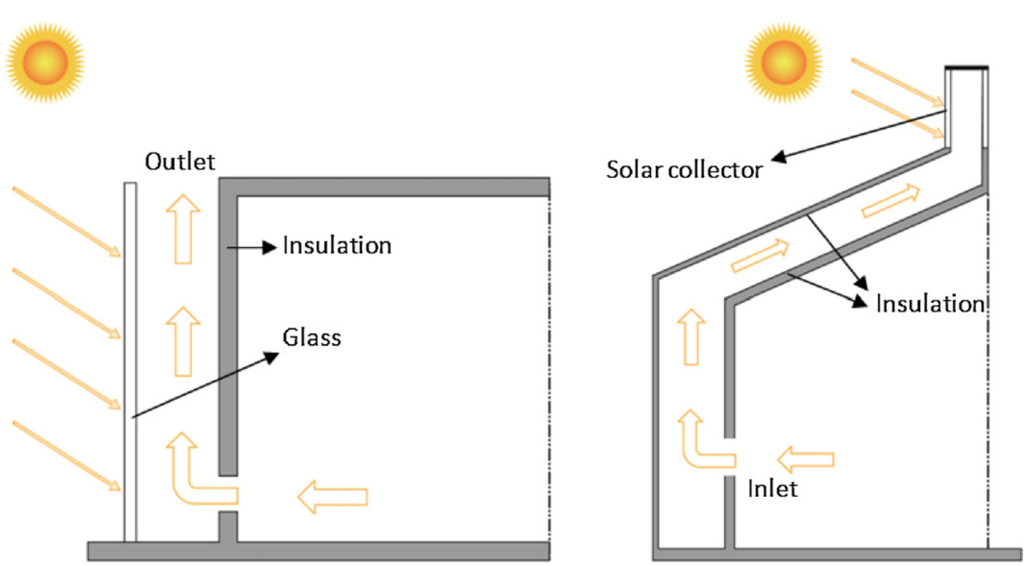


**Fig. 3.** Schematic of two kinds of solar chimney: vertical solar chimney (left); and roof solar chimney (right).

**Table 2**
Advantages and disadvantages of two types of solar chimney.

| Type | Advantages | Disadvantages |
|---|---|---|
| Vertical solar chimney | • The external glass gain sun radiation, solar collector is not needed;<br>• The air flow in chimney could go upward directly without bends;<br>• Easier to be control with inlet and outlet for different climatic condition; and<br>• Stack height is not restricted by roof height. | • Insulation is need to prevent direct heat transfer between chimney and interior room because of high temperature and high contact area; and<br>• Barriers are strictly prevented because the solar gained wall is lower than roof solar collector; |
| Roof solar chimney | • Very large collector areas easily achieved;<br>• May be more aesthetically pleasing than a tower;<br>• No additional towers needed;<br>• Likely to be cheaper than a tower design; and<br>• Easier to retrofit. | • Stack height is restricted by roof height;<br>• Heat transfer between heated air and glass is higher than for a vertical surface;<br>• Additional bends create greater pressure-losses; and<br>• Incorporation of thermal mass may be more difficult. |

factors such as the location, climate, and orientation can also affect its performance [29].

Analytical method has been used to calculate velocity of air flow in a solar chimney. In order to describe average air velocity inside solar chimney as a function of system parameters, two different expressions have been gained [27,30–32]. The first one is derived by assuming that pressure head inside a tilted chimney counter-balances completely the pressure drop due to the wall friction and inlet and outlet pressure losses. The average velocity is expressed by:

$$v = \left[ \frac{2L \cdot g \cdot (\sin\theta)^2 (\rho_{out} - \rho_{in})}{(f \cdot (L/D_H) + k_{in} + k_{out}) \cdot \rho_{in}} \right]^{1/2} \quad (1)$$

where $L$ is the length of chimney, m; $g$ is gravitational acceleration, 9.8 m/s$^2$; $\theta$ is the slope with respect to horizontal plane,°; $\rho_{out}$, $\rho_{in}$ are the density of air from environmental and interior room, respectively, kg/m$^3$; $k_{in}$ and $k_{out}$ are inlet and outlet pressure loss coefficients, respectively.

The $D_H$ and $f$ in Eq. (1) are hydraulic diameter and wall friction coefficient for turbulent flow, which are expressed by:

$$D_H = \frac{2w \cdot d}{w + d} \quad (2)$$

$$f = \frac{0.316}{Re^{1/4}} \quad (3)$$

where $w$ is the width of chimney gap, m; $d$ is the depth of chimney gap, m; and Re is apparent Rayleigh number. For a rectangular channel with both ends open and heated on one wall, it is proposed $k_{in}$ = 1.5, $k_{out}$ = 1.0 and $f$ = 0.056.

The second expression is an empirical relation which uses concept of a discharge coefficient to adjust the air velocity for the total flow resistances in the system (friction losses along the chimney wall, inlet and outlet pressure losses, etc.). For a case of equal cross sectional area at the inlet and outlet of the chimney this relation reduces to:

$$v = C_d \frac{\rho_{out}}{\rho_{in}} \left[ \frac{L \cdot g \cdot (\sin\theta)^2 \cdot (T_{out} - T_{in})}{T_{in}} \right]^{1/2} \quad (4)$$

where $C_d$ is discharge coefficient, this value was proposed as 0.57 for thermal buoyant flows; $T_{out}$ and $T_{in}$ are temperature of air from environment and interior room, respectively, K.

Inclination angle of solar collector has effects to the performances of solar chimney. Harris and Helwig [28] analyzed the impacts of inclination angle on the induced ventilation rate. The numerical results showed that for a south-facing chimney, an inclination angle of 67.5° from the horizontal was optimum, giving 11% greater efficiency than vertical chimney in Edinburgh, Scotland (latitude 52°). Bassiouny and Korah [33] gained that an optimum air flow rate value was achieved when chimney inclination is between 45° and 70° for latitude of 18.4° by using analytical method. Hamdy and Fikry [34] showed that an angle of 60° stands for the ultimate performance for north latitude of 32°. Previous research concluded the optimum inclination angle for maximizing airflow depends on latitude of the location, shown in Table 3 [29]. It is found that these optimum angles are from 40 to 60°.

The performances of solar chimney also depend on air gap width. Andersen [32] proposed that channel width for solar chimneys should be at least 4.7 cm, and airflow rate increases for large cavity widths up to 0.2–0.3 m. Zhai et al. [35,36] found back-flow in an experimental set up with a 0.2 m gap. Miyazaki et al. [37] showed that air gap width of solar chimney hardly affected mass flow rate induced by buoyancy when air gap width is more than 0.2 m. However, Gan [38,39] claimed rising flow rates for cavities larger than 0.3 m where the inlet breadth is the same size as cavity width. Bassiouny and Korah [33] found that chimney width from 0.1 m to 0.35 m is acceptable when solar intensity greater than or equal to 500 W/m$^2$ by using numerical method.

Other aspects are also analyzed by researchers to enhance the performance. Lee and Strand [40] used numerical simulation found that: (1) chimney height, solar absorptance and solar transmittance turned out to have more influences on natural ventilation improvement than air gap width; (2) the higher thermal chimneys with greater absorber wall solar absorptance and the glass cover solar transmittance result in larger building natural ventilation enhancement; and (3) climatic conditions of particular locations have significant impacts on the overall performance. Afonso and Oliveira [41] used experiments and simulations found that: (1) it is fundamental to use outside insulation in brick wall, to take advantage of solar gains. If outside insulation is not used, solar assistance efficiency reduced by more than 60%; and (2) a insulation thickness of 5 cm is sufficient, and no significant improvements can be achieved with thickness above 10 cm.

Configurations of solar chimney in high-rise building have been analyzed by Punyasompun et al. [42]. Two design configurations were considered in three-floor building. The first is a tall solar chimney with an inlet opening at each floor and one outlet opening at the third floor, and the second with an inlet and outlet openings at each floor. Small-scale experimental results showed that the best

**Table 3**
Optimum inclination value for maximizing airflow depends on latitude of the location.

| Latitude (°) | Optimum inclination (°) | Latitude (°) | Optimum inclination (°) |
|---|---|---|---|
| 0 | 55 | 35 | 50 |
| 5 | 50 | 40 | 50 |
| 10 | 50 | 45 | 55 |
| 15 | 50 | 50 | 55 |
| 20 | 45 | 55 | 60 |
| 25 | 45 | 60 | 60 |
| 30 | 45 | 65 | 60 |

**Table 4**
Summary of research on solar chimney.

| Method | Major study parameters | | | | Results | | | Major findings/limitations |
|---|---|---|---|---|---|---|---|---|
| | AR | $w$ (m) | $\theta$ (°) | $I$ (W/m$^2$) | ACH | Flow rate | Flow velocity | |
| Analytical | N.A. | 0.14 | 30 | 200–1000 | 3–6 | 100–350 m$^3$/h | N.A. | N.A. |
| Analytical | N.A. | 0.15 | 30 | 700 | 60 | 1.4 kg/s | N.A. | • Solar chimney assisted wind tower can provide adequate ventilation; • Stack effect in the wind tower not considered. |
| Experimental | N.A. | 0.14 | 15, 30, 45 | 150–350 | N.A. | 0.08–0.15 (m$^3$/sm$^2$) | N.A. | N.A. |
| Analytical | 13.8 | 0.145 | N.A. | 100–600 | N.A. | 0.014 kg/s at $I$ = 400 W/m$^2$ | N.A. | • Air temperature increases indefinitely with wall length; • Unable to predict the temperature variation on the wall. |
| Experimental and analytical | N.A. | 0.13 | N.A. | 200–700 | N.A. | N.A. | 0.25–0.39 m/s at $I$ = 650 W/m$^2$ | • Solar chimney with 0.3 m air gap provide more ventilation than 0.1 m gap; |
| Analytical | N.A. | 0.13 | N.A. | 700 | N.A. | N.A. | 0.24 m/s | • Window size solar chimney can improve ventilation; |
| Experimental | 1:152:5 | 0.1–0.40.6 | 15, 30, 45, 60 | 200–600 | N.A. | 0.032 m$^3$/s at $I$ = 400 W/m$^2$ $b$ = 0.2 m, $\theta$ = 45 | N.A. | • A chimney with 1.5, height, 0.2 m air gap width and 45° inclination give higher flow rate than vertical one; |
| Numerical | N.A. | 0.35 | 15, 30, 45, 60, 75 | 500–750 | N.A. | N.A. | N.A. | • Correlation for ACH is valid only for $I \geq$500 W/m$^2$; |

*Note*: *AR* is aspect ratio; *w* is air gap width; $\theta$ is the absorber inclination angle; *I* is the solar intensity; and *ACH* is air changes per hour.

configuration is that with an inlet opening at each floor and one outlet opening at the third floor as temperature difference between rooms and ambient was the lowest.

Some important research findings are summarized in Table 4 [29].

## 3. Ground source-based energy systems

### 3.1. Ground source heat pump

#### 3.1.1. Theory

Ground source heat pump (GSHP) system is a renewable energy technology highly efficient for space heating and cooling. This technology relies on the fact that, at depth, the Earth has a relatively constant temperature, warmer than the air in winter and cooler than the air in summer. It can transfer heat stored in the Earth into a building during the winter, and transfer heat out of the building during the summer [43].

The adoption of GSHP systems may result in primary energy consumption reduction up to 60% compared to convectional heating and cooling systems [44]. Comparison of different heating systems is shown in Table 5 [43].

A typical GSHP system consists of heat pump(s) to heat/cool the building, a ground heat exchanger (GHE) to collect/reject heat to the ground, and pump(s) to circulate a thermal fluid between the heat pumps and the GHE [45]. Fig. 4 shows the layout of a GSHP system for heating [43].

**Table 5**
Comparison of different heating systems.

| System | Primary energy efficiency (%) | $CO_2$ emissions (kg $CO_2$/kWh heat) |
|---|---|---|
| Oil fired boiler | 60–65 | 0.45–0.48 |
| Gas fired boiler | 70–80 | 0.26–0.31 |
| Condensing gas boiler + low temperature system | 100 | 0.21 |
| Electrical heating | 36 | 0.9 |
| Conventional electricity + GSHP | 120–160 | 0.27–0.30 |
| Green electricity + GSHP | 300–400 | 0.00 |

The GSHP systems can be divided into two categories, depending on type of operation, autonomous or in combination with a conventional heating or cooling system, referred as hybrid system [44]. In the autonomous system, heat pump is connected to GHE, vertical or horizontal, or to the underground or surface water aquifer, and it supplies the building with required heating and cooling energy. Obviously, system is properly designed in order to cover the heating and cooling loads of buildings, even under extreme weather condition. The hybrid systems combine ground source energy system (heat pump and GHE) with a conventional heat (e.g. oil or natural gas boiler) or cool (e.g. cooling tower) source. Systems of this type should be preferred in cases where length of GHE required for heating is significantly larger than the one for cooling, or vice versa.

#### 3.1.2. Design and energy saving

Analysis of thermal response test data makes use of the line source theory. The temperature response of fluid can be approximated using the following formula, given in [46]:

$$T_f(t) = \frac{Q}{4\pi\lambda_{eff}H}\ln(t) + \left[\frac{Q}{H}\left(\frac{1}{4\pi\lambda_{eff}}\left(\ln\left(\frac{4\alpha t}{\gamma^2}\right) - \gamma\right) - R_b\right) + T_i\right] \quad (5)$$

where $T_f$ is circulation fluid temperature, K; $Q$ is heat injection/extraction, W; $\lambda_{eff}$ is the effective thermal conductivity, W/K m; $H$ is length of the borehole heat exchange, m; $\alpha$ is thermal diffusivity, W/m K; $\gamma$ is Euler's constant, 0.5772; $R_b$ is borehole resistance, m K/W; and $T_i$ is undisturbed ground temperature, K.

Implementation is by determining the slope of average fluid temperature development versus the natural log of time curve:

$$T_{ave}(t) = s \cdot \ln(t) + b \quad (6)$$

where $T_{ave}$ is the average between the inlet and outlet temperature, K; $s$ is the slope of the curve; and $b$ is the $y$-intercept of the curve.

To calculate the effective thermal conductivity, this formula has to be transformed:

$$\lambda_{eff} = \frac{Q}{4\pi Hs} \quad (7)$$

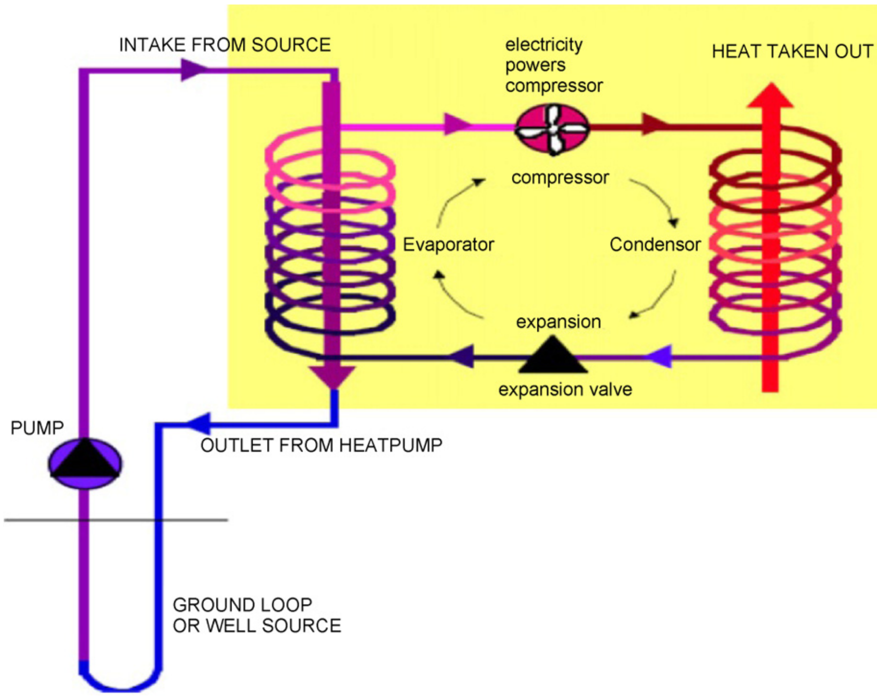


**Fig. 4.** Layout of a GSHP system for heating.

Ground's temperature is changed along the depth, which can be given as follow [47]:

$$T_0 = T_d + A_d \exp\left[-y\frac{\Omega}{2a}\right] \cos\left[\Omega t - y\frac{\Omega}{2a}\right] \tag{8}$$

where $T_0$ is the ground's natural temperature (°C) at depth $y$ (m) at time $t$; $T_d$ is the mean Earth's surface-temperature (°C) between the hottest and the coldest months; $A_d$ is the amplitude (°C) of the Earth's surface temperature; $\Omega$ is the frequency, rad/h; and $a$ is the thermal diffusivity, W/m °C.

Many analytical methods can be used for GSHP system. These analytical methods can be seen in Refs. [48–50] in detail.

Coefficient of performance (COP) describes the performance of a GSHP system, which is the ratio of heating or cooling to the energy consumed by the system. The higher COP means the more efficient of the system. The COPS is the COP of whole system.

Large amount of research focused on GSHP systems to find the optimum performance in building. Table 6 shows a summary of typical research. Several results are needed to be addressed:

- GSHP systems mainly depend on operating conditions, economical viability, environmental impacts, etc.;
- Exergy loss of a GSHP system for building heating model is bigger than that of cooling model, and the exergy efficiency of a whole GSHP system is obviously lower than those of its components for both building heating and cooling modes;
- Compressors should be chosen carefully because maximum exergy loss happens here;
- Vertical type GSHP systems can be preferred where the costs of drilling are low;
- The COP and COPS seems to be lower in typical spring and autumn weather conditions when comparing to summer and winter conditions; and
- Care must be taken in the design and construction of a ground loop to ensure long ground loop life and reduce the installation costs.

## 4. Day-lighting system

### *4.1. Side-lighting system*

#### *4.1.1. Theory*

*4.1.1.1. Side window.* Side window is the simplest way in side-lighting. Daylight gained is proportional to the area of window's opening. The best way to gain more daylight is to increase the number of windows and their area, such as side windows and clerestory. Fig. 5 shows daylight penetration resulting from the combination of a vertical clerestory and a side window.

Several shortcomings hamper their applications. Firstly, daylight gained depends on the area of window or clerestory. Some buildings do not have enough area for windows openings. Secondly, daylight concentrates on area near the windows and it decreases as room is deeper. Thirdly, windows cannot automatically control the daylight if the sun is excessive which makes occupants uncomfortable.

*4.1.1.2. Light shelf.* A light shelf is a device designed to capture daylight, particularly sunlight, and redirect it towards the back of the room by reflecting it off the ceiling [59]. The light shelf could control the intensity of sunlight with different solar elevation angle. When daylight is lower in the room, the light shelf could adjust the angel to let the sunlight reflect to the ceiling of the room, then the ceiling provides additional diffuse light to help give uniform illumination and also allows sunlight to penetrate deeper into the room. Furthermore, the light shelf can provide shade from direct sunlight and decreases glare from the outside. Fig. 6 shows the daylight penetration in a room with an oblique light shelf.

*4.1.1.3. Louver system.* Louver systems are designed to capture sunlight falling in the front of room and redirect it towards the back, thereby increasing daylight levels in the back of the room and reducing them in the front [59]. The louver system can be divided into two types: static and dynamic. The dynamic type works dynamically as the sun moves, and its efficiency is much higher than static type. This dynamic type needs calibration which

**Table 6**
Summary of research on GSHP systems.

| Method | Location | System parameters | Results | Major findings/limitations | Refs. |
|---|---|---|---|---|---|
| Experimental | Erzurum, Turkey | Vertical GHE<br>Diameter 32 mm[a]<br>Depth 53 m | Yearly average COP 3.1<br>Yearly average COPS 2.7 | • GSHP system mainly depends on operating conditions, economical viability, environmental impacts, etc. | [51] |
| Experimental | Northern Greece | 21 vertical boreholes (37 on a 4.54.5 grid)<br>Depth 80 m<br>Diameter 40 mm | COP for heating 4.4–5.2<br>COP for cooling 4.5–4.4 | • Energy required for heating and cooling is largely reduced compared to air-to-water heat pump based system and conventional oil boiler. | [52] |
| Numerical | Izmir, Turkey | Vertical GHE<br>Depth 50 m | COP 3.12–3.64<br>COPS 2.72–3.43 | N.A. | [53] |
| Numerical | Beijing, China | N.A. | N.A. | • Maximum exergy loss ratio is in compressor, and minimum exergy efficiency and thermodynamic perfect degree is the GHE; and<br>• Exergy loss of a GSHP system for building heating model is bigger than that of cooling model, and the exergy efficiency of a whole GSHP system is obviously lower than those of its components for both building heating and cooling modes. | [54] |
| Experimental | Denizli, Turkey | Vertical GHE<br>Length 225 m<br>Depth 110 m | COP 3.1–4.8<br>COPS 2.1–3.1 | • Vertical type GSHP systems can be preferred where the costs of drilling are low; | [55] |
| Experimental | Elazig, Turkey | Horizontal GHE<br>Depth 1 or 2 m | COPS 2.66 (1 m depth)<br>COPS 2.81 (2 m depth) | • Care must be taken in design and construction of a ground loop to ensure long ground loop life and reduce installation costs. | [56] |
| Experimental | South Korea | Vertical GHE;<br>24 boreholes<br>Depth 175 m | COP about 8.3<br>COPS about 5.9 | • COPS was found to be lower than COP because COPS included the energy consumed by GSHP system with additional water circulating pumps and fans. | [57] |
| Numerical | Shanghai, China | Vertical GHE<br>Depth 80 m<br>Diameter of borehole 160 mm | COP 3.0, COPS 1.5 (Spring)<br>COP 5.4, COPS 3.0 (Summer)<br>COP 2.5, COPS 1.0 (Autumn)<br>COP 5.2, COPS 1.0 (Winter) | • The COP and COPS was lower in typical spring and autumn weather conditions when comparing to summer and winter conditions. | [58] |

[a] Diameter and length which are not pointed out refer to the pump.

depends on the weather and geographic conditions. Fig. 7 shows a light-redirecting louver system.

*4.1.1.4. Prismatic glazing.* Prismatic glazing is designed to change the direction of incoming sunlight and redirect it by way of refraction and reflection [59]. As daylight penetrate through the prism, its direction change due to the refraction. One part of the daylight goes to the ceiling then reflects to the deeper room. Actually, this prism allows the daylight penetrate much further to the room comparing to the side room. The other part of daylight goes directly to the near-window place. The distribution of daylight in the room is controlled by occupants' requirement and do not gather in one place. Fig. 8 shows a prismatic panel inserted within a side window.

### 4.1.2. Design and energy saving

*4.1.2.1. Side window.* Energy consumption of lighting in building is a major contributor to carbon emissions, often estimated as 20–40% of the total building energy consumption. Jenkins and Newborough showed that annual energy savings for lighting of 56–62% and a reduction in $CO_2$ emissions of nearly 3 tonnes by using side windows in a typical 6-storey office building [60]. Also Arumi [61] mentioned that window sizing as well as proper selection of external surface to volume ratio can result in 50% total energy savings for heating, cooling and lighting to windowless configuration.

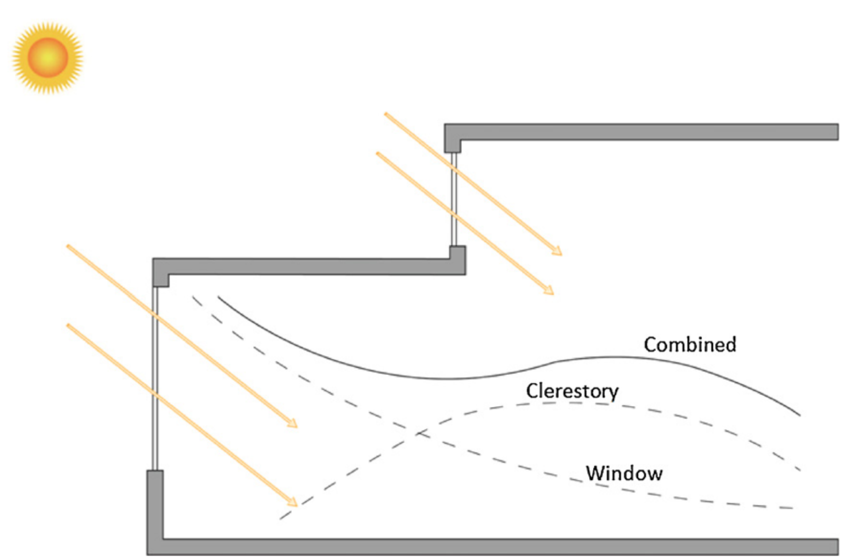


**Fig. 5.** Daylight penetration resulting from the combination of a vertical clerestory and a side window.

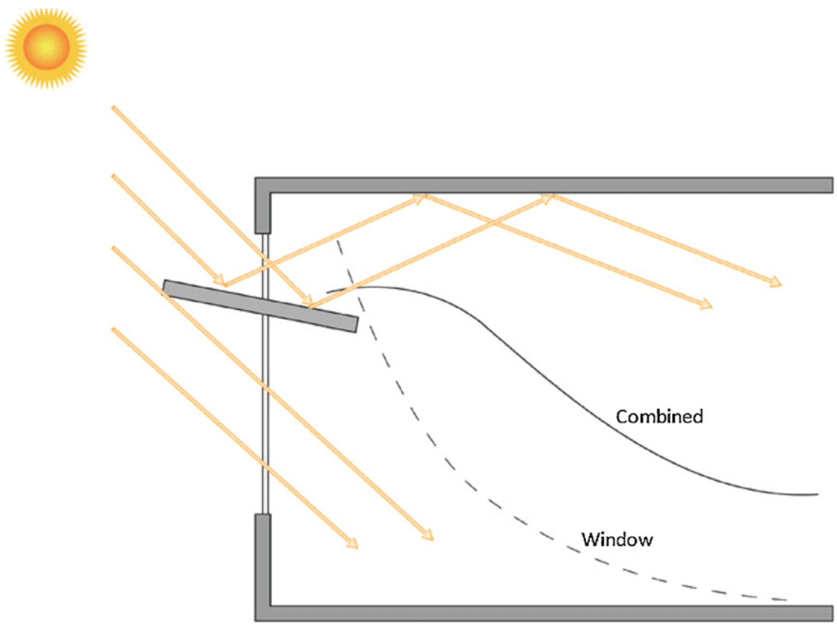


**Fig. 6.** Daylight penetration in a room with an oblique light shelf.

Performance of side window is dependent on several factors, such windows area, transmittance, angle, etc. Daylight penetration factor (DPF), which shows windows' performance, can be expressed as follow [60]:

$$DPF = \frac{\tau C A_g \theta O}{A_T(1-R^2)} \quad (9)$$

where $\tau$ is the transmittance of glazing, $0 \leq \tau \leq 1$; $C$ is correction factor for glazing due to dust, poor maintenance, seen in Table 7 [60]; $A_g$ is the area of glazing, $m^2$; $\theta$ is vertical angle of visible sky from horizon,°; $O$ is orientation factor for glazing, seen in Table 8 [60]; $A_T$ is total area of room surface, $m^2$; and $R$ is average reflectance of all room-surfaces, $0 \leq R \leq 1$.

Windows glazing are used together with PV panels in order to get a better performance. Miyazaki et al. [62] investigated a PV

**Table 7**
Correction factor ($C$) for dirt on glazing.

| Description of glazing | Vertical | Sloping | Horizontal |
|---|---|---|---|
| Clean | 0.9 | 0.8 | 0.7 |
| Very dirty | 0.7 | 0.6 | 0.5 |
| Industrial conditions | 0.8 | 0.7 | 0.6 |

**Table 8**
Orientation factors ($O$) for glazing.

| Orientation | Factor |
|---|---|
| Horizontal | 1.00 |
| North | 0.97 |
| East | 1.15 |
| South | 1.55 |
| West | 1.21 |

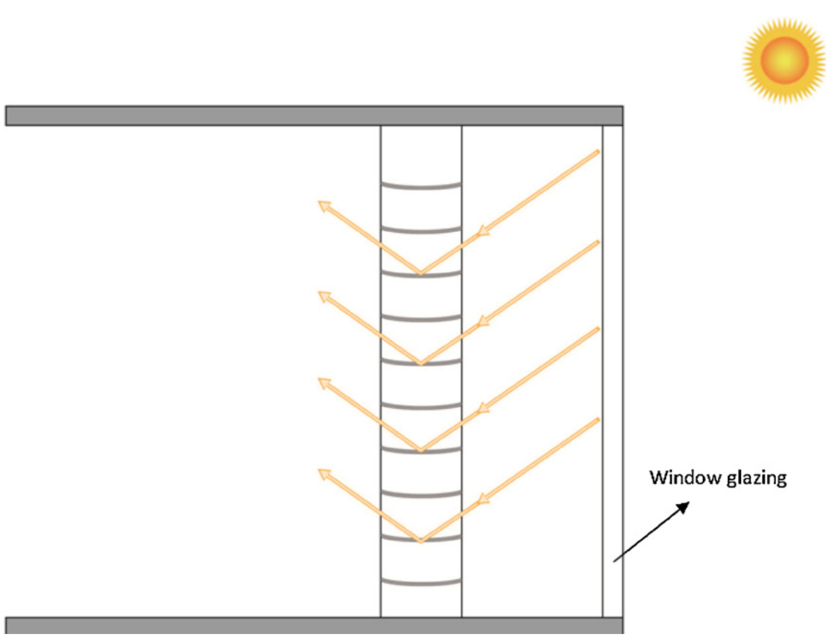


**Fig. 7.** Light-redirecting louver system.

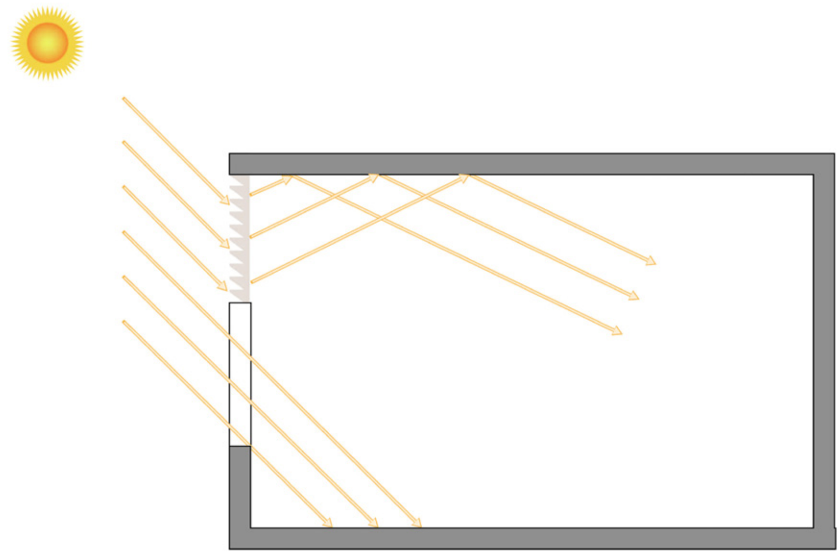

**Fig. 8.** Prismatic panel inserted within a side window.

window which consists of a double glazed window with semi-transparent solar cells. Results showed that solar cell transmittance of 40% and window to wall ratio (WWR) of 50% achieve the minimum electricity consumption, which was reduced by 55% when comparing to single glazed window with WWR of 30%. Chow et al. obtained that solar cell transmittance in PV window in a range of 0.45–0.55 could achieve the best electricity saving in Hong Kong.

Eletrochromic glazing also can be utilized to reducing energy consumption and discomfort glare without compromising much of the available daylight. Piccolo and Simone [63] showed that for south facing windows enhanced daylight control provided by electrochromics light modulation could be suitable for maintaining acceptable visual comfort condition in indoor environment. Lee et al. [64] obtained that the electrochromics glazing control system could maintain interior illuminance levels to within 510–700 lx for 89–99% of the day, and save more energy than normal glazing. Sullivan et al. [65] gained that energy saving for a large electrochromics window can be as large as 90 kWh/m$^2$. Other research concentrated on electrochromic glazing can be seen in Refs. [66–70] in detail.

*4.1.2.2. Light shelf.* Light shelf can throw all the energy of direct sunlight into the interior space. In contrast, using shading to tame sunlight for day lighting leaves most of the potential day lighting energy outside the building. To design a well-organized function of light shelf needs [71]:

- A good treatment of windows. Portion of window below the light shelf needs separate treatment to prevent glare. The window must be exposed to direct sunlight to be an applicant for a light shelf.
- The simplest materials and function of light shelf such reflector. It could be as simple as aluminum foil taped to a piece of cardboard.
- Distribution function of day lighting is from the portion of the window that extends above the light shelf. Bottom portion of window contributes daylight only to the thin zone under the light shelf. The window must face towards the sun for a large part of the time, and outside objects cannot shade it. If the window glazing is tinted or reflective, the day lighting potential is reduced substantially.
- Ceiling is another and vital distribution form of sunlight, which is received from light shelf. The ceiling then distributes the light to the occupants. The ceiling plays the same role as the electric lighting equipment. In most cases, the ceiling should be highly reflective to save as much light as possible. Height and orientation of the ceiling and the diffusion characteristics of the ceiling distribute the daylight.

Littlefair [72] revealed that an internal light shelf could improve the uniformity of daylight in a room and provide some solar shading, but without significantly increasing illuminances at the back of the room. Experimental results suggested that light shelves should be as reflective as possible, and to work best need a high ceiling. Also light shelves perform best in a room with external obstructions, when they can increase core illuminances by around 15%.

Other important parts of designing a light shelf are material and position under sunlight. Claros and Soler [73–77] have done a lot of work by using a 1:10 model to analyze the performances of light shelf in Madrid, Spain. The results showed that: (1) for four types of light shelf, such as row aluminum painted with three layers of white matte, white opaque methacrylate, mirror, and row aluminum, the methacrylate light shelf performed better than the mirror light shelf for the central months of the year, while the mirror light shelf performed better for about the first three months and last three months of the year; (2) the methacrylate light shelf gave the smallest range of interior illuminance values throughout the year; and (3) light shelf with vertical shade angle of 50° showed its best performance when solar azimuth between 60° and 70°.

*4.1.2.3. Louver system.* Angle of louvers has affects to the performances of louver systems. Hammad and Abu-Hijleh [78] used software to evaluate the overall performance energy consumption of a representative office with external louvers on the south, east and west oriented facades in Dubai. Simulations carried out on static horizontal louvers showed that the optimal static was −20° for the south oriented facade with a total energy saving of 31.28%. And the optimal angle for vertical louvers on the east and west facades was 20° and resulted in a total energy savings of 26.08% and 25.97% on the east and west facades, respectively. The plan view showing angles of horizontal and vertical louver slats can be seen in Fig. 9 [78].

Ceiling geometry also has influences on the performances of louver systems. Freewan et al. [79] gained that the best ceiling shape is the one that is chamfered in the front and rear of the room, and illuminance level increased in the rear of the room and decreased in the front – near the window, compared to the room having horizontal ceilings.

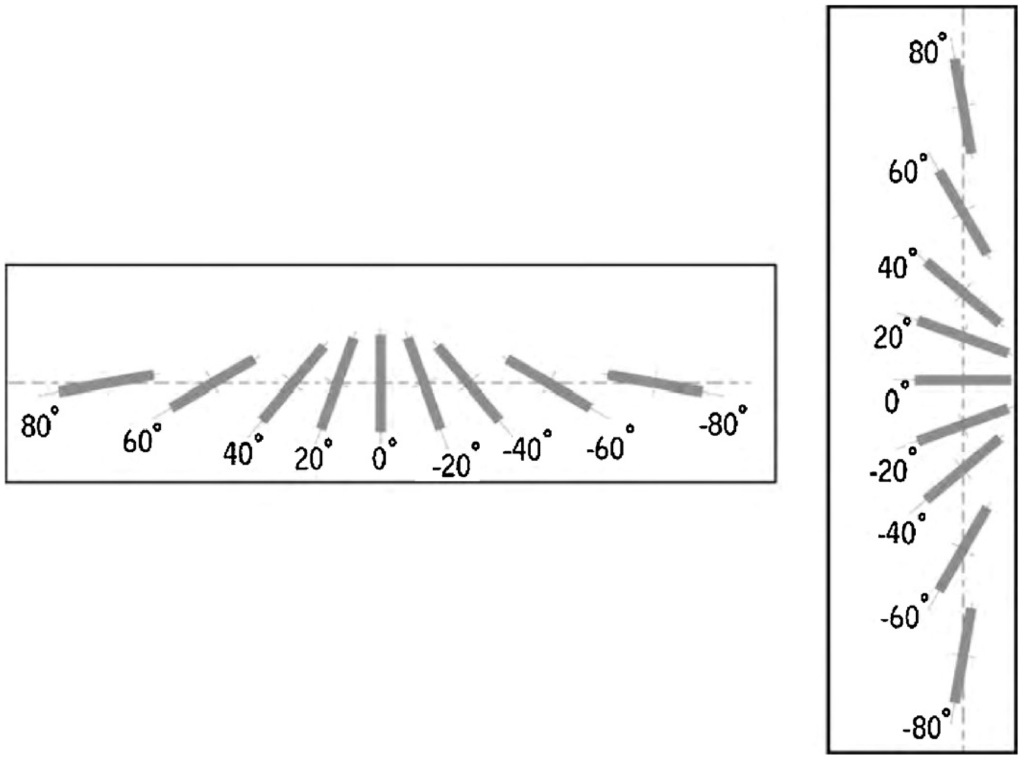


**Fig. 9.** Plan view showing angles of horizontal and vertical louver slats.

Performance of the louver shading device for some hot places in summer is necessary. Studies [80–84] showed that integration of louver shading devices in buildings leads to indoor comfortable thermal conditions and may lead to significant energy saving. The effect of louver shading devices on building energy requirements depends on several factors. In particular, location, louver inclination angle and window area have special importance when trying to guarantee thermal comfort conditions [80].

*4.1.2.4. Prismatic glazing.* Prismatic systems are usually made of acrylic, typically in elements of 206 mm × 206 mm. Generally, they are protected against dust and mechanical damage by two glass panes, or, if used in the clerestory, by being embedded in a double-glazing unit. Recently, projects were employed using unprotected prismatic system, but the prisms had to be orientated downwards to avoid collecting dust and dirt [85].

With prismatic glazing higher efficiency seasonal shading can be realized. They are suitable for vertical, south-facing windows or facade elements, preferably in applications which do not need a free view, for example, high windows or windows in factories and sports halls. The direct radiation received on a vertical south-facade is reduced to 10% on clear summer days, while 90% is transmitted on clear winter days [86].

To achieve the main functions of sun screening and daylight distribution, prismatic system works with reflection and refraction. Many types of prismatic system with different angles of prism are used according to the location in building. They are produced either clear or with a part-silvered prism (one face of the prism is coated for total reflection). Clear systems need a one-axis tracking system due to a limited cut-off range for direct sunlight (±4.5° in relation to the perpendicular). Using fix panels, the specular surface on one side has to guarantee that all direct sunlight angles are within the panel's cut-off range [85].

*4.2. Top-lighting system*

*4.2.1. Theory*

*4.2.1.1. Skylight system.* Skylight system is one of the simplest top-lighting strategies. It usually provides a horizontal or slanted opening in the roof of a building and is designed to capture sunlight when the sun is high in the sky and diffuse light from the zenithal area of the sky vault, and introduce it into the portion of the room under the skylight. This day-lighting system can be used only for the top floor of a multi-story building or for single-story building [59]. Daylight penetration pattern from two skylights is shown in Fig. 10.

*4.2.1.2. Roof monitor and sawtooth system.* Roof monitor and sawtooth systems are top-lighting systems that differ primarily in their shapes. Under these systems, light is captured through vertical or sloped openings in the roof. These openings can be designed to capture sunlight at certain times of the day or of the year, depending on the requirements of the building [59]. Fig. 11 shows a daylight distribution under roof monitor. In this system, winter sunlight can penetrate into the room because of low angle of the Sun, and summer sunlight cannot enter under the shelf of roof monitor. Also, two-side roof monitor is used to make a more even sunlight distribution. Fig. 12 shows a single-sided sawtooth system, which has a similar mechanism with roof monitor.

*4.2.1.3. Light pipe system.* Light pipe system is made up of a skylight dome, a reflective tube, and a diffuser assembly. The dome should be UV and impact resistant, it protects the tube from dust and rain [87]. Two types of light pipe systems are commonly used, one is straight and the other is elbowed. The light pipe system usually has three parts. At the top of this system is a clear dome, which is used to gain sunlight from exterior environment. The second part is made up of one or several connected light reflecting tubes. This part is aim to reflect the sunlight into the interior spaces. The last

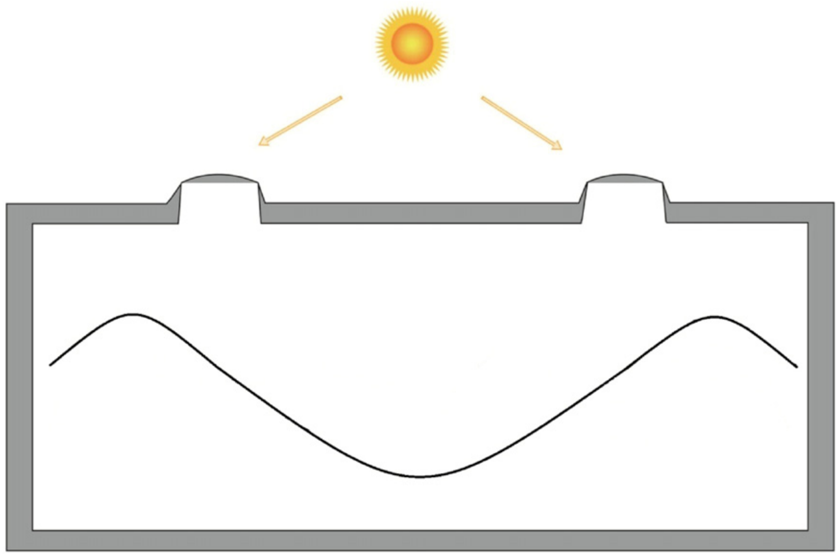

**Fig. 10.** Daylight penetration pattern from two skylights.

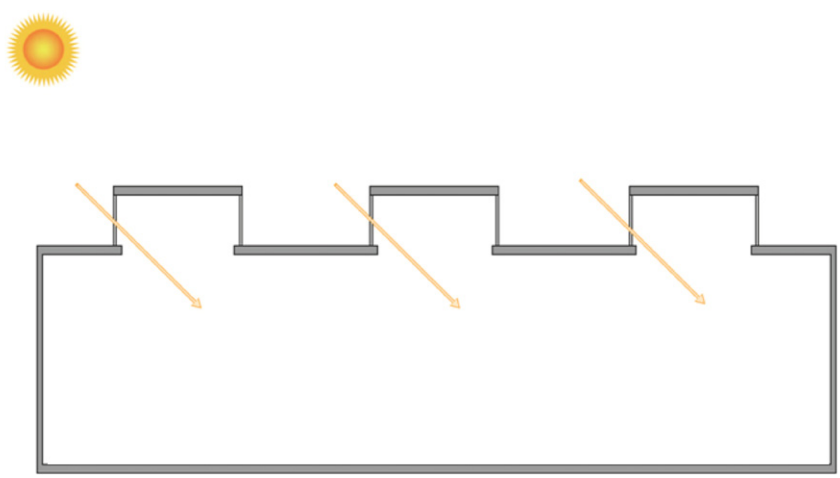

**Fig. 11.** Daylight distribution under roof monitor.

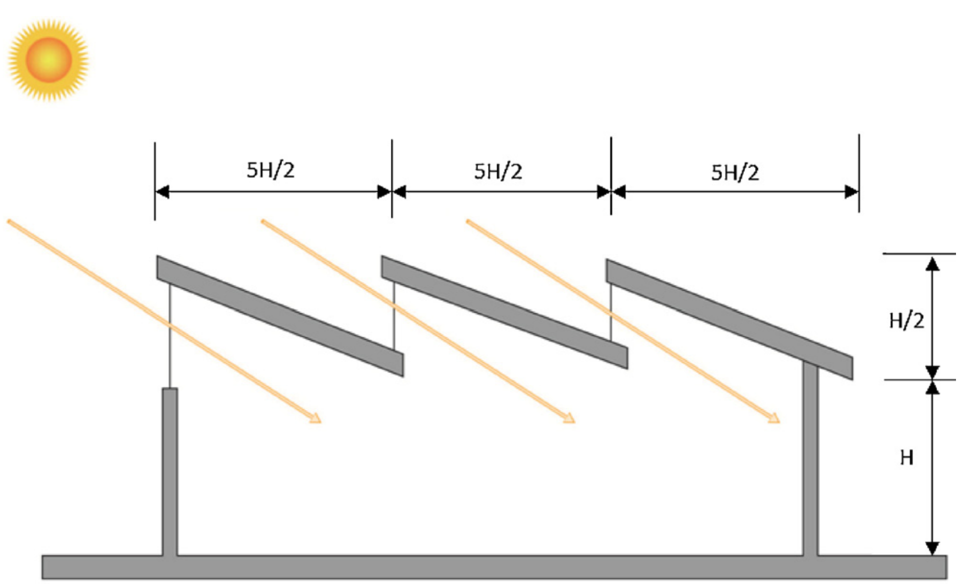


**Fig. 12.** A single-sided sawtooth system provides directional distribution of daylight inside the room.

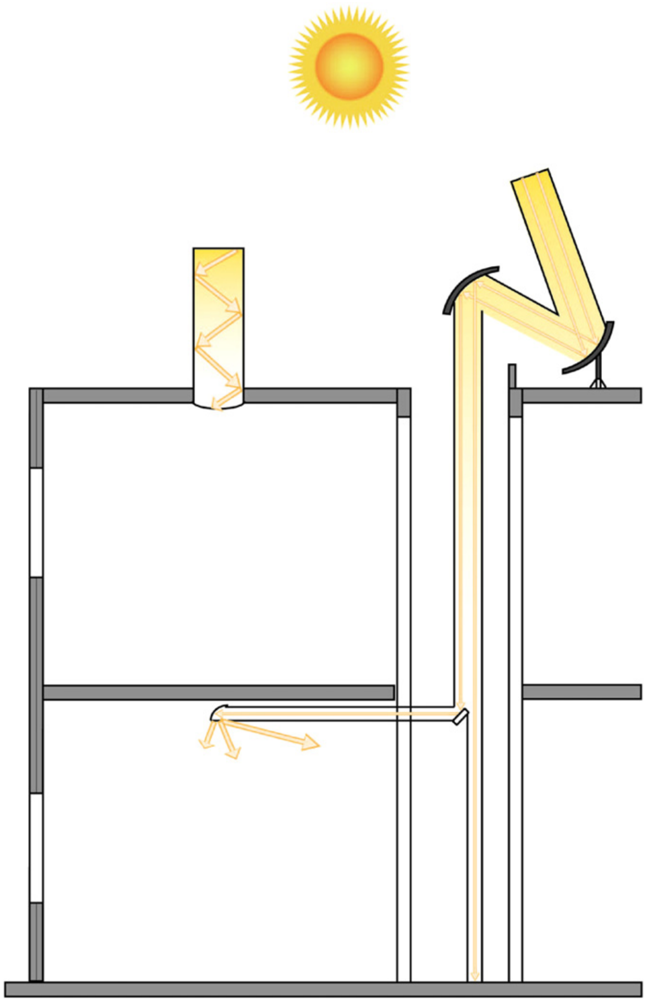

**Fig. 13.** Schematic diagram of light pipe systems: a straight light pipe (left); a light pipe with bends (right).

**Table 9**
Coefficients used in Zhang's models.

| Models | $a_0$ | $a_1$ | $a_2$ | $a_3$ | $a_4$ | $a_5$ | $a_6$ |
|---|---|---|---|---|---|---|---|
| Eq. (10) | 62.5 | −17.2 | 2.6 | 136.0 | 4.3 | 1.1 | −0.4 |
| Eq. (11) | 192.5 | −108.8 | −0.3 | 132.4 | 4.4 | 8.6 | −2.6 |

part is the diffuser which is installed on the ceiling in the interior room to be illuminated. Schematic diagram of two types of light pipe systems is shown in Fig. 13.

*4.2.2. Design and energy saving*

*4.2.2.1. Skylight system.* Laouadi et al. [88,89] used a computer simulation program to predict the impact of design alternatives on the annual cooling and heating energy of skylight system in cold climate. These design alternatives are fenestration glazing types, fenestration surface area, skylight shape, atrium type, and interaction of the atrium with its adjacent spaces, which are shown in Fig. 14 [89]. Some results are needed to be highlighted:

- Fenestration glazing type. Double clear glazing yielded the highest annual total energy ratio and triple clear low-e glazing the lowest annual total energy ratio. As compared with the basecase design, the double clear glazing reduced annual total energy ratio by up to 7%, triple clear glazing by about 19–24%, double gray glazing by about 23–35%, double clear low-e glazing by about 27%, and triple clear low-e glazing by about 41%.
- Fenestration surface area. As compared with an atrium with 100% glazed roof and walls, a 50% reduction in the fenestration surface are reduced annual cooling energy ratio by about 51–58%.
- Skylight shape. As compared with the flat skylight, the pyramidal skylight for the three-sided atrium reduced annual cooling energy ratio by up to 19%. Pitched skylight for linear atrium increased annual cooling energy ratio by up to 12%. Effect of skylight shape on annual heating energy ratio was dependent on the solar heat gain coefficient (SHGC) and $U$-value of the fenestration.
- Adjacent space. As compared with a closed atrium space, an open atrium space reduced annual cooling energy ratio by about 62–70% for enclosed atrium, by about 34–40% for three-sided atrium and by about 22–27% for linear atrium. Annual heating energy ratio of the open atrium space was also reduced by up to

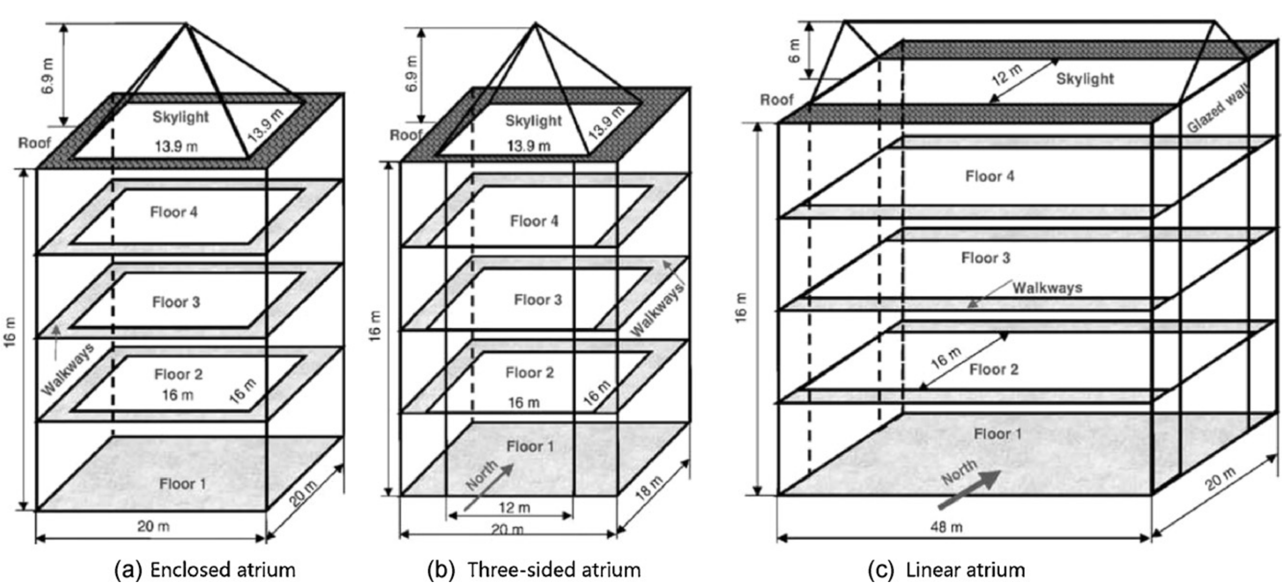


**Fig. 14.** Atrium shapes as simulated with pyramidal/pitched skylight and 100% glazed roof and walls.

**Table 10**
Experimental results of light pipe under different geographic locations.

| Parameters | Seasons | Average illuminance (lx) | DPF (%) | Location of experiments | Refs. |
|---|---|---|---|---|---|
| Diameter: 0.25 m[a] Length: 1.0 m | Spring | 263 | 0.37 | Ancona, Italy | [87] |
| | Summer | 435 | 0.50 | | |
| | Winter | 43.8 | 0.38 | | |
| Diameter: 0.25 m Length: 2.8 m | Winter | 8–55 (overcast sky)200–400 (clear sky) | 0.21 | Hong Kong | [101] |
| Diameter: 0.65 mLength: 1.32 m | – | 238 (overcast sky) 510 (clear sky) | 0.680.64 | South Korea | [102] |
| Diameter: 0.33 m Length: 4.0 m | Summer | 409 | 0.30 | Nottingham, UK | [103] |
| Diameter: 0.33 mLength: 2.77 m | Summer | 440 | 0.50 | Nottingham, UK | [103] |

[a] Diameter is the diameter of top dome, and length is the length of reflecting tube. All of the light pipes in this table are straight light pipe.

6% for the linear atrium. The annual heating energy ratio for the enclosed and three-sided atriums increased by up to 19%.

The fenestration options, such as skylights, windows, and clerestories, have the influence to building space heating, cooling, and lighting loads. Different fenestration options are examined by Treado et al. [90] by using simulation in Washington, DC. The main findings of this research are: (1) skylights are the most effective fenestration options, and with 2% of roof area being the optimum size; (2) skylight are the most effective day-lighting source, reducing electric energy by as much as 77% as compared to non-daylighting cases; (3) clerestories are more effective than windows with same size; and (4) south-facing clerestories and windows are more effective than north-facing ones, and 50% clerestory and window areas are most effective.

Some experiments are used to analyze daylight penetration factor (DPF) in New Delhi, India [91,92]. It is obtained that yearly average values of DPF for big and small dome skylight are determined as 2% and 6%, respectively. And total annual average artificial lighting energy saving potential was estimated as 973 kWh/year, which is equal to 1526 kg/year of $CO_2$ emission.

The skylight system also can be used combined with other systems, such as PV system [93], electrochromic glazing [94], etc.

*4.2.2.2. Roof monitor and sawtooth system.* Several zenithal solar passive strategies, such as skylight, roof monitors and clerestory roof windows, were analyzed by their possible energy savings and better performance by Garcia-Hansen et al. [95] in Mendoza, Argentina. Experimental results showed: (1) in the thermal aspect, solar saving fraction is 41.4% for roof monitors and 38.86% for skylights for a glass area of 9% to the floor area; (2) for daylight analysis, skylights are recommended for cloudy sky types, and clerestory roof windows for clear sky types, however, roof monitors gave the best results under variable sky conditions; and (3) the roof monitors had the best combined results in terms of lighting and thermal effects.

Sawtooth systems are excellent day-lighting strategy when uniform daylight distribution is required throughout a large room or work surface. There is directionality in light distribution under these systems especially on clear days and if the opening is facing south. On an overcast day, sawtooth system provides a little more uniformity than on clear days [96]. In general daylight levels are higher towards the end of the room that faces the opening. The spacing between sawteeth is recommended to be 5H/2, with H being the height of the ceiling clearance, shown in Fig. 12.

*4.2.2.3. Light pipe system.* Illuminance of interior room depends on weather conditions. The interior illuminance would be higher when the sky is clear, comparing to an overcast or part-overcast sky. Zhang et al. [97] developed a mathematical model to predict day-lighting performance achievable by light pipe with two types under weather conditions. The DPF of straight light pipe is expressed as:

$$DPF_{straight} = (a_0 + a_1 k_t + a_2 \alpha_s)\rho^{(a_3 + a_4 A_p + a_5 \cot\ \alpha_s + a_6 A_p \cot\ \alpha_s)} \frac{R^2 (H/D)^m}{D^2} \tag{10}$$

where $a_i$ are coefficients gained by experiments, which are shown in Table 9; $\alpha_s$ is the solar altitude; $k_t$ is clearness index of the sky, which is defined as ratio of global to extra-terrestrial irradiance; $R$ is the radius of the light pipe; $\rho$ is the surface reflectance of light pipe; $A_p$ is the aspect ratio, which is defined as ratio of light pipe length to diameter; $H$ is the vertical height of light pipe diffuser above the working plane; and $D$ is the distance from light pipe diffuser centre to a given position.

The DPF of elbowed light pipe is given as:

$$DPF_{elbowed} = (a_0 + a_1 k_t + a_2 \alpha_s)\rho^{(a_3 + a_4 A_p + a_5 \cot\ \alpha_s + a_6 A_p \cot\ \alpha_s)} \frac{R^2 (1 - f_{loss})(H/D)^m}{D^2} \tag{11}$$

where $A_p = (L + f_{len} L_b)/2R$ and $L$ is the length of straight light pipe, $f_{len}$ is the equivalent-length factor, $L_b$ is the sum of linear lengths of bends, and $f_{loss}$ is the energy-loss factor for each 30-° bend.

Other models are also used to predict DPF of light pipe, such as Jenkins et al. model, and CIE model. The details can be found in Refs. [98,99].

Experiments were taken to find out a better performance with light pipe system [100]. These experimental results under different geographic location are listed in Table 10.

With the development of modern building, light pipes are not used solely, which also exists with its integration with solar heating and natural ventilation. This kind of design would provide a better performance to occupants for its multi-function [104–109].

## 5. Conclusions

This paper reviewed the state of the art in designing renewable energy systems, namely solar-based energy system, ground source-based system and day-lighting system, to gain optimum performances in sustainable buildings.

For solar-based energy systems, it is obtained that geometric conditions, such as local weather condition, altitude, latitude, have a determining effect on system's performance. Designing factors, such as system selection (BIPV or BIPVS system), building's orientation, installation location (wall, rooftop, or window glazing), area of installation, tilt angle, surface temperature, are needed to be considered when designing a PV system. Designing a better performance of solar chimney is to increase pressure difference between interior room and outside environment, including height, width and depth of cavity, type of glazing, inclination angle of solar collector, type of absorber, insulation, and configuration.

For ground source-based energy systems, operating conditions, system modes (heating, cooling, or both of them), selection of compressor, GHE (vertical or horizontal), season conditions, pump

(diameter, depth), are important to improve system's performance and reduce the cost.

To optimize the quality of the luminous environment for occupants, weather still is the determining condition. Selection of day-lighting systems must consider local weather conditions. Designing factors of side-lighting and top-lighting systems, such as fenestration option, material, area or size, shape, orientation, position, ceiling, shading devices, are needed to be considered carefully.

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